Three-Dimensional Seismic Interpretation of Near-Seafloor Salt Bodies and Fluid Expulsion Features Adjacent to the Mississippi Canyon, Gulf of Mexico

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By

Kain Lager-Lowe
The Ohio State University
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Approved by

Dr. Derek E. Sawyer, Advisor
School of Earth Sciences

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Abstract

Seismic interpretation is one of the first things that are done after a seismic data set has been attained and processed. This interpretation acts as a guideline to where possible drilling hazards would be located and could be used as a starting point for further research into future drilling expeditions in the area. For this thesis, I obtained a public 3-D seismic dataset from the U. S. Geological Survey National Archives of Marine Seismic Surveys that is located near the Mississippi Canyon in the northern Gulf of Mexico and that imaged a variety of near-seafloor features that had not been previously described in the scientific literature. I focused on the analysis and interpretation of three seafloor features based on their prominent amplitude anomalies and structural properties. Feature #1 contained a halo-like amplitude anomaly and is interpreted as a gas seep in which underlying salt facilitated upward fluid migration to the surface. Feature #2 has a consistent circular anomaly that was determined to be a salt diapir extruding at the seafloor. Feature #2 also contained a bottom simulating reflector which may indicate the presence of gas hydrate. Feature #3 had no amplitude anomaly but rather an elevation anomaly that is likely gas-free roof sediments overlying the same salt diapir that affected features #1 and #2. A key finding made possible with three-dimensional seismic data is that the salt body is one continuous body, not individual bodies. The near-seafloor conditions in this study area suggest that fluid flow, gas, and salt tectonics are active in the present-day.

Acknowledgements

I would first like to thank my advisor, Derek Sawyer for all of his help and guidance throughout the process of writing this thesis. I would also like to thank him for sparking my interest in reflection seismology through his truly stimulating and hands on course here at Ohio State. Without this course, I am not sure when or if I would have gotten exposure to this area of geology that I enjoy so much.

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I also thank IHS KingdomSuite software that I used in this study that was available under the academic license agreement with Ohio State.

I am forever grateful to my family for all of their love and support throughout my life and educational career. I would also like to acknowledge all of the support and help my friends have provided throughout my life. I would not be who or where I am today without the help of all of these wonderful people.

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Introduction

The Gulf of Mexico (GOM) is a prominent area for oil and gas exploration. Through the use of seismic data information relating to natural hazards and hydrocarbon prospects can be assessed. These hazards include drilling risk assessments as well as any seafloor and subsurface geologic structure that could be detrimental to drilling operations. Seismic data can be interpreted in order to find out which areas need further investigation and which areas are promising gas and oil plays. This thesis is an example of a seismic interpretation using two-way time (TWT) anomalies, amplitude anomalies and seismic profiles. In this thesis I utilize three-dimensional multi-channel seismic data to interpret the seafloor and near-seafloor subsurface geology. Because seismic data alone are generally not suitable for direct interpretation of rocks and fluid properties, future work from this seismic analysis could be complemented by integration of well logs from previous drilling, if available, to provide additional constraints on the nature of the sediments and fluids. The study area had no public drilling expedition data so there is no ground truthing being done in this interpretation nor any well logs being used. This thesis could be used to determine if further investigation needs to be done in the areas in question if a drilling operation were to take place.

Geologic Setting

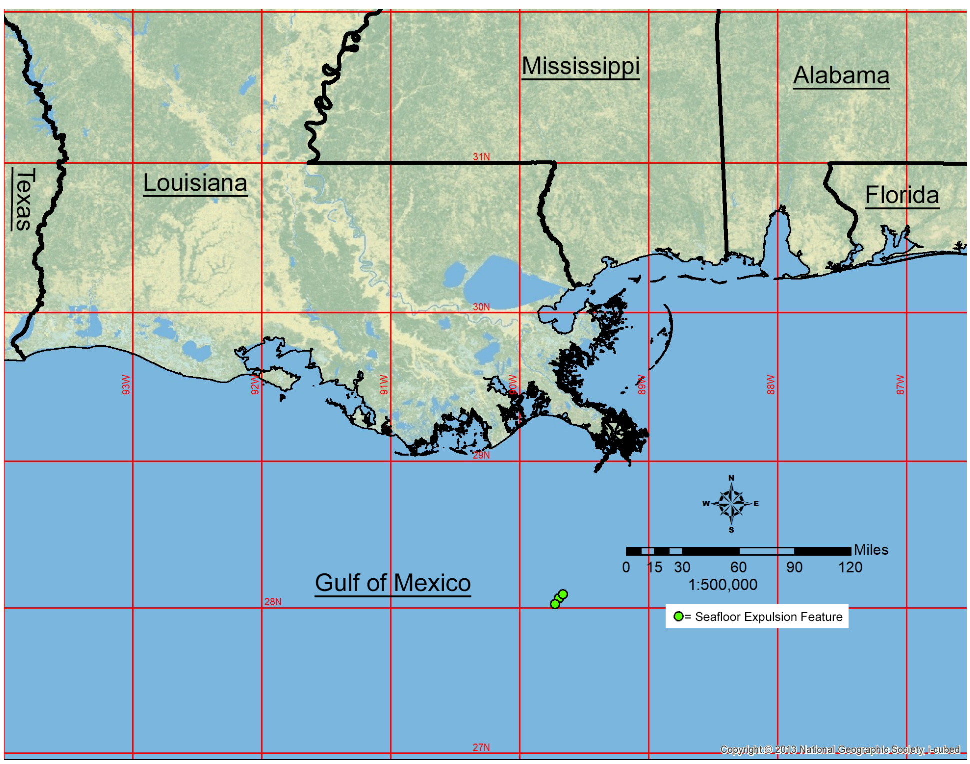

Figure 1: Map of GOM showing expulsion features sites. Map created in ArcGIS v.10.2.

In a classic tectonic sense, the GOM is described as a passive margin. The basin first opened in the Jurassic where a thick salt layer accumulated and then was buried by continental sediment in the late Jurassic and carbonate sediments late in the Cretaceous (Worrall and Snelson, 1989). Later in the Neogene there was a large load of sediments deposited from terrestrial sources that created a continental margin sedimentary wedge that was roughly 16km thick (Sager et al., 2003). The rough topography within the GOM can be attributed to the role of salt tectonics in the subsurface (Sager et al., 2003). Salt is a highly incompressible material and for that reason the sediment load occurring during the Neogene in the northern GOM caused the salt layers to go southward and its relatively low density (2.4 g/cc) also promoted the salt to buoyantly rise in stratigraphy (Humphris, 1979). This has caused a multitude of faults, mini basins and seafloor features relating to salt tectonics. The strain within units of salt tectonics can be seen as a viscous flow due to their incompressible nature (Hudec and Jackson, 2007). Salt is buoyant when denser rocks are emplaced above causing all types of faults and topographic expressions (Hudec and Jackson, 2007). Conduits and faults that have been deformed by salt tectonics can act as pathways for fluid migration (Kennicutt et al., 1988). This migration of salt in the subsurface can also cause seals that allow oil and gas to accumulate. Features related to salt tectonics and hydrocarbon accumulations can be imaged in seismic data sets and can be identified as areas for further analysis.

Methods

Importing 3D Seismic Data

The seismic data set, B-101-91-LA, was acquired from the U.S. Geological Survey (USGS) (Table 1). The 3D Multichannel Seismic (MCS) survey was originally acquired in 1991 by the Bureaus of Oceans Energy Management for oil and gas exploration in U.S. Outer Continental Shelf (OCS) using an air gun and hydrophone streamer set up. The dataset was then transferred to the USGS for posting on The National Archive of Marine Seismic Surveys (NAMSS) webpage under the terms of procurement which states that the data are to be available to the public 25 years after the issuance of the exploration permit and can now be publicly found at https://walrus.wr.usgs.gov/namss/survey/b-101-91-la/. The 3D MCS data were loaded into IHS KingdomSuite using the loading metadata provided in the data set download.

Seafloor Horizon Map

After the dataset was loaded properly, the seafloor horizon was mapped. The seafloor was selected inline by inline and then cross line by crossline throughout the whole survey to get a detailed and accurate seafloor map. The seafloor was mapped based on the first strong positive impedance contrast in contact with sea water. After the seafloor was fully mapped, features of interest were determined.

Establishing Features to Analyze

Three seafloor features were chosen. The areas were chosen because of amplitude anomalies and subsurface geology associated with said anomalies. Structural contours were created using Kingdom Suite, at a contour interval selected of 0.0351s TWT, chosen because it best-illustrated the topography of the seafloor features.

Visual Images

Representative seismic lines were interpreted to determine the subsurface geology. Two-way time (TWT) base maps and amplitude base maps were extrapolated and analyzed to determine the connection between the surface geology and amplitude anomalies. The scales on the base maps were adjusted to represent the features being shown. These base maps were then integrated with the seismic lines to combine subsurface geology with amplitude anomalies and relief features to illustrate what is controlling said features that are exposed at the modern-day seafloor. The three-dimensional viewer, VuPAK, in IHS Kingdom Suite was utilized to show cross-sectional cubes that helped to connect the chosen seismic lines with surface seafloor features on base maps to correlate the driving factors on the geomorphology of the seafloor. VuPAK was also used to show the seafloor features from different angles. Seismic lines were annotated using Adobe Illustrator and Adobe Photoshop. The publicly available dataset of Kramer and Shedd (2017) was loaded into ArcGIS and used to create a hill shade bathymetry map of the seafloor used in figure 6. ArcGIS was also used to create the location map of the Gulf of Mexico used in figure 1. The locate function in ArcGIS was used with coordinates taken from the seismic data in IHS Kingdom Suite in order to mark the given features on the bathymetry and location maps.

Data Interpretation

Seismic Lines are in a black-to-white variable density scale. Black will always correlate to a positive impedance contrast while white will always correlate to a negative impedance contrast.

TWT base maps are in a scale that represents TWT time in seconds. The shallowest TWT on the scale is 0.790s while the deepest TWT on the scale is 1.300s. These values were chosen because the tops of the features that were selected have a TWT of around 0.790s while the deepest TWT represented is around 1.05s. The deep end value of 1.300s was chosen to give a gradient scale that would show relief within the features in question. The shallower TWT will be red on the map and scale while a deeper TWT will correlate to blue. Smaller TWT means shallower while larger TWT correlates to deeper below the sea surface. The other base map that is shown is an amplitude base map that shows the respective amplitude throughout the mapped seafloor. This map will have areas where more positive amplitudes that are shown in red and less positive amplitudes that are shown in blue. The high amplitude anomaly corelates to a value of 30,000 and the low-end amplitude anomaly correlates to 0. This range of values were chosen because one feature chosen correlates with a high amplitude anomaly while other features show neutral amplitudes, this range captures both ends of the amplitude anomalies that were trying to be showcased. Color bars and scales will be provided respectively for seismic lines and base maps.

Table 1: Information for the Seismic Survey

Survey	Year	Weblink
B-101-91-LA	1991	Https://walrus.wr.usgs.gov/namss/survey/b-101-91-la/

Results

Three features were chosen for analysis because they were located in areas that contained amplitude anomalies or elevation anomalies. Two of the features were chosen due to amplitude anomalies and a third feature was chosen because of an elevation anomaly.

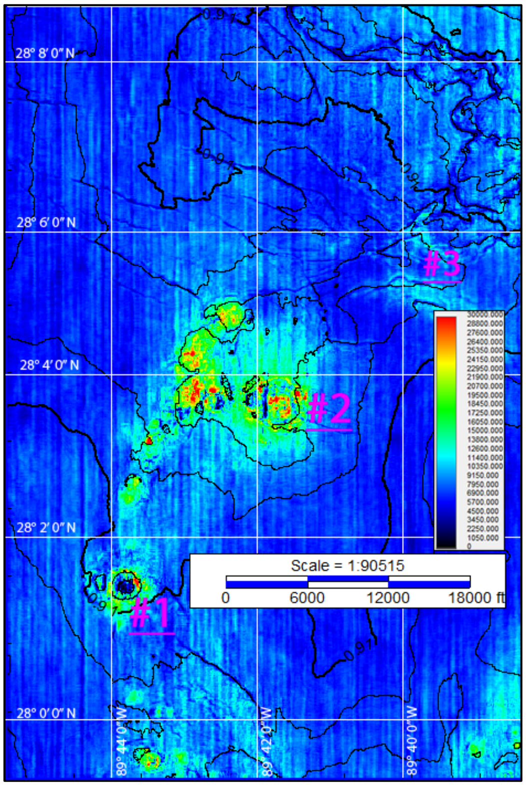

Figure 2: Amplitude base map of Seafloor. Red Correlates to a high amplitude. Blue Correlates to a low amplitude. The three features of interest are labeled with numbers respectively.

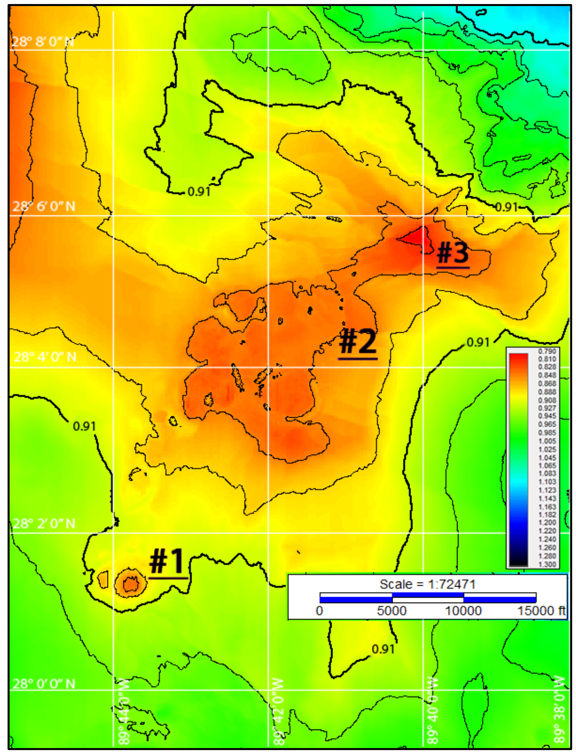

Figure 3: TWT base map of Seafloor. Red Correlates to a lesser TWT and a shallower depth below the sea surface. Blue Correlates to a greater TWT and a greater depth below the Surface. The three features of interest are labeled with numbers respectively.

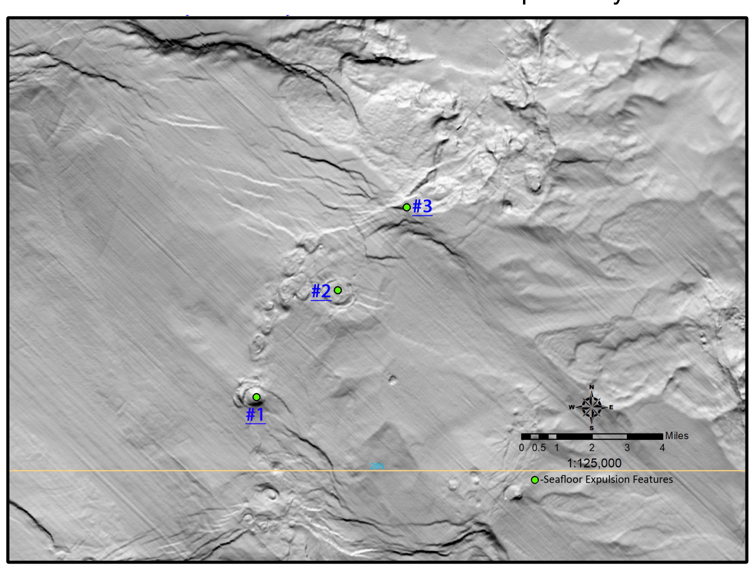

Figure 6: Hill shaded bathymetry of Seafloor Features. Located in the Mississippi Canyon off shore from Louisiana. Map created in ArcGIS using the dataset of Kramer and Shedd, (2017).

Seafloor Feature #1

The first feature was chosen because it has a halo like amplitude anomaly on the amplitude base map (figure 2) that is in conjunction with a hill like topography on the TWT base map (figure 3). This area is a topographic high in the immediate vicinity of feature #1. This is shown on a cross-sectional view of the feature and on the TWT base map (figures 3 & 4). The total change in TWT of the feature is 0.160 s. Created contour intervals fit the feature and show the topography of a hill type shape. On a cross-sectional view we also see transparent facies beneath this seafloor feature with some bedding still preserved. The preserved bedding is mostly cut off by the flanks of the transparent area (figure 4). The preserved bedding looks as if it has been very slightly folded upward. The amplitude anomaly is high around the outer ring of the feature and low in the center (figure 2). There is also a smaller mound to the west of the main feature. When the VuPAK view is correlated with a seismic profile it shows the relationship between topography, the seafloor and the transparent body beneath the seafloor (figure 4).

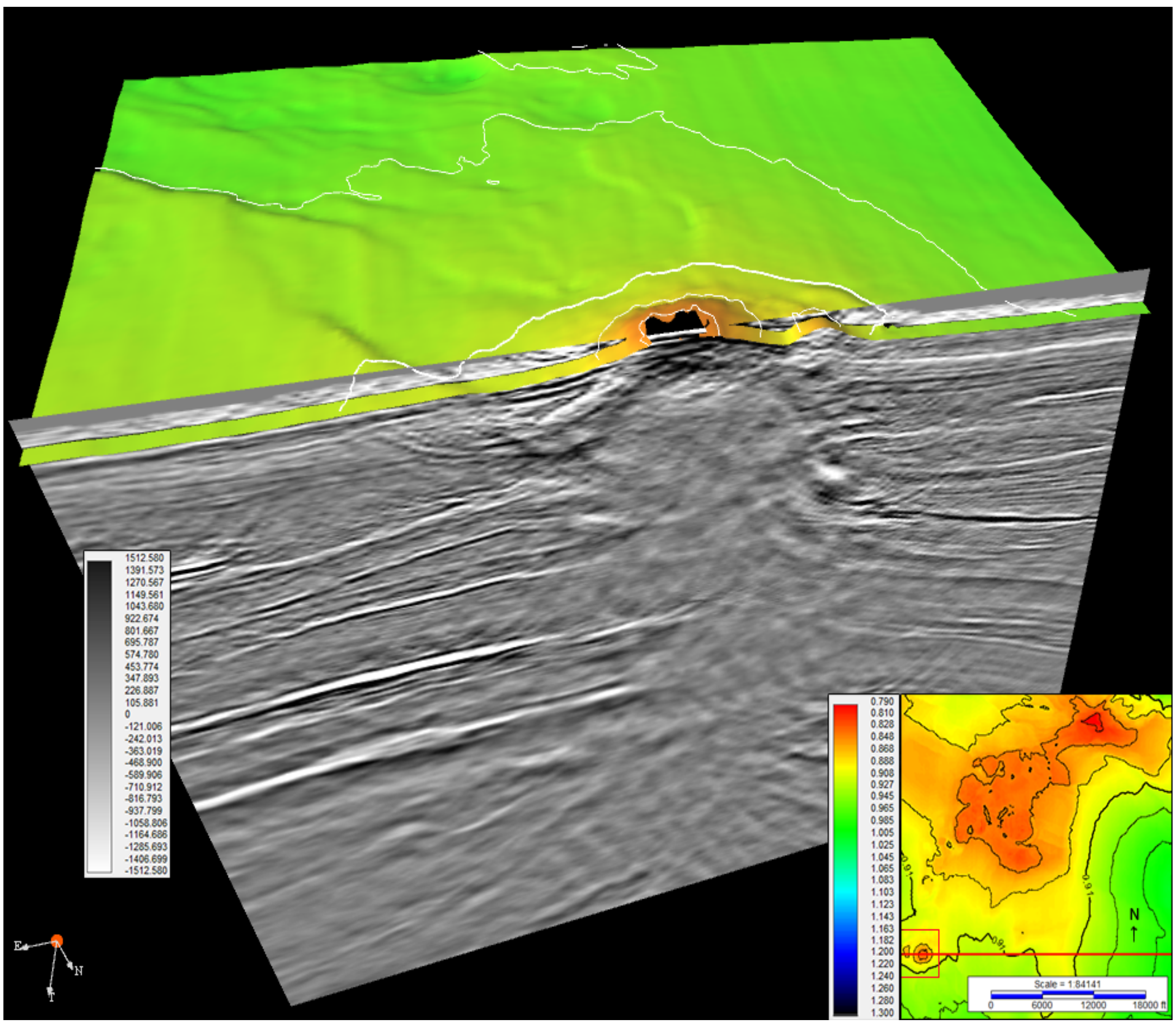

Figure 4: Uninterpreted VuPAK of feature #1. Cross-sectional view shown with overlying topography to connect subsurface geology with topographic expressions. There is some bedding preserved but most is muddled by the transparent facies in the subsurface. The red square on the map is the topography imaged in VuPAK while the red line is the seismic line being shown.

Seafloor Feature #2

The second feature was chosen because it had a high positive amplitude anomaly and was located on a plateau-like feature. Unlike feature #1 this feature has a relatively constant high positive anomaly across the entire feature (figure 2). The created contour intervals show this area as a topographic high with a plateau style that stays relatively the same height (figure 3). The total change in TWT of this feature is around 0.100 s making it less drastic a change than seen in feature #1. The cross-sectional view reinforces the change in topography and shows another transparent facies beneath this feature. Bedding is cut off by the flanks of the transparent area and looks as if the flanks of the bedding have been folded upward to a greater magnitude than in feature 1 (figures 4 & 5). The transparent area reaches all the way to the seafloor (figure 5). Within the transparent area there is a strong negative reflector (figure 5). In the bathymetric map of the seafloor it is possible to see radial faulting around feature #2 (figure 6). The VuPAK view when correlated with seismic profiles shows the relationship with topography of the seafloor and the transparent body beneath the seafloor (figure 5).

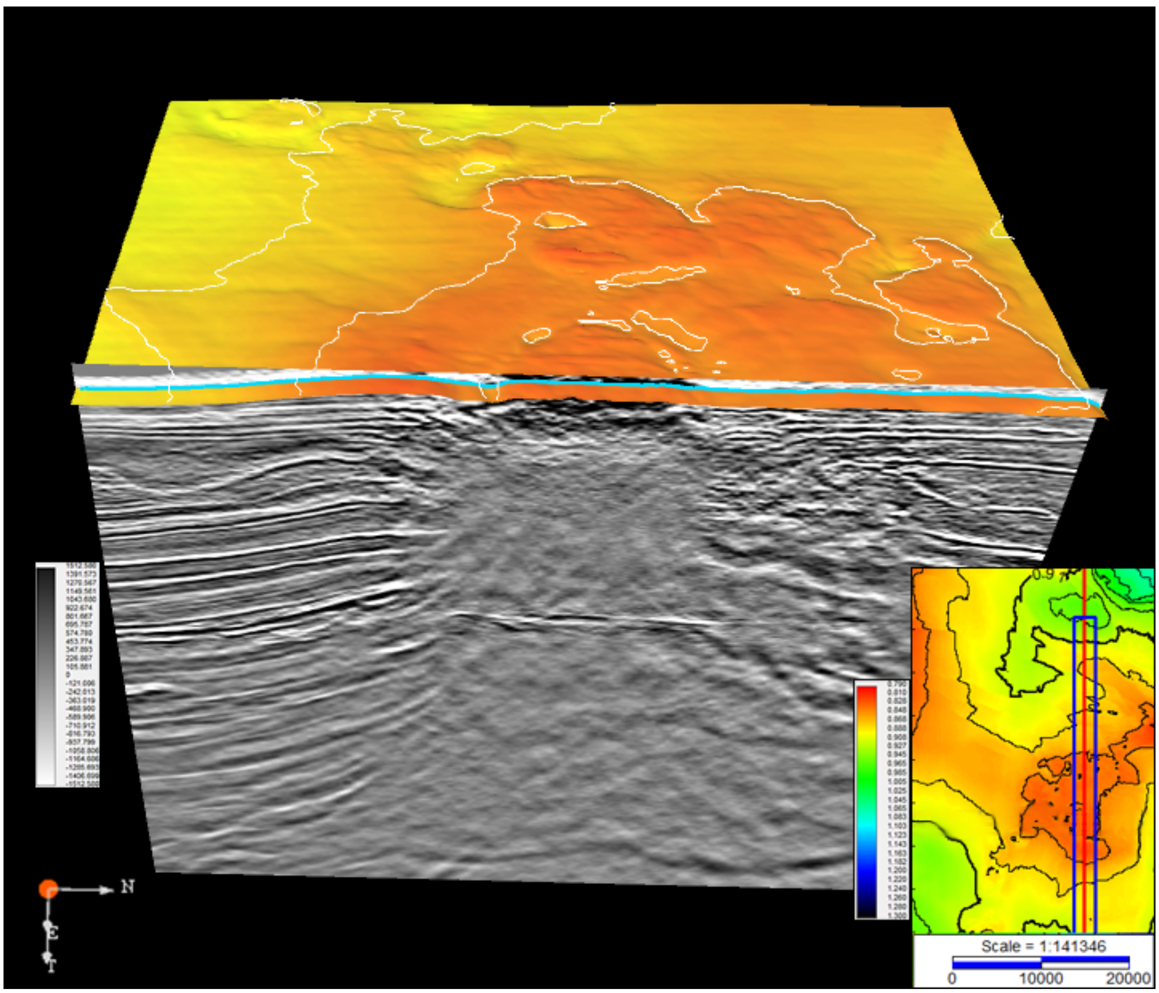

Figure 5: Uninterpreted VuPAK of feature #2. Cross-sectional view shown with overlying topography to connect subsurface geology with topographic expressions. There is no bedding preserved as it is muddled by the transparent facies in the subsurface. There is a strong negative reflector present in the middle of the transparent facies. The red line is the seismic line in VuPAK.

Seafloor Feature #3

The third feature was chosen because it had a high elevation anomaly with no amplitude anomaly. This feature reaches a height of 0.790s and is the top member TWT color bar scale that was established. The created contours show hill-like topography and the TWT base map concurs with this (figure 3). On the amplitude base map there is no anomaly and it seems that feature #3 has the same amplitude as the majority of the modern-day seafloor (figure 2). Cross-sectional views through the feature show bedding that is uplifted and undercut by a large transparent facies (figure 7). This transparent facies is clearly underlying layers of bedding and is not exposed at the seafloor. There is a fault that starts at the transparent facies and outcrops at the seafloor on the south western flank of the feature in question. In the bathymetric map of the seafloor it is possible to see sets of faulting around feature #3 (figure 6). The VuPAK view when correlated with seismic profiles shows the relationship with the raised topography of the seafloor and the transparent body beneath the seafloor (figure 7).

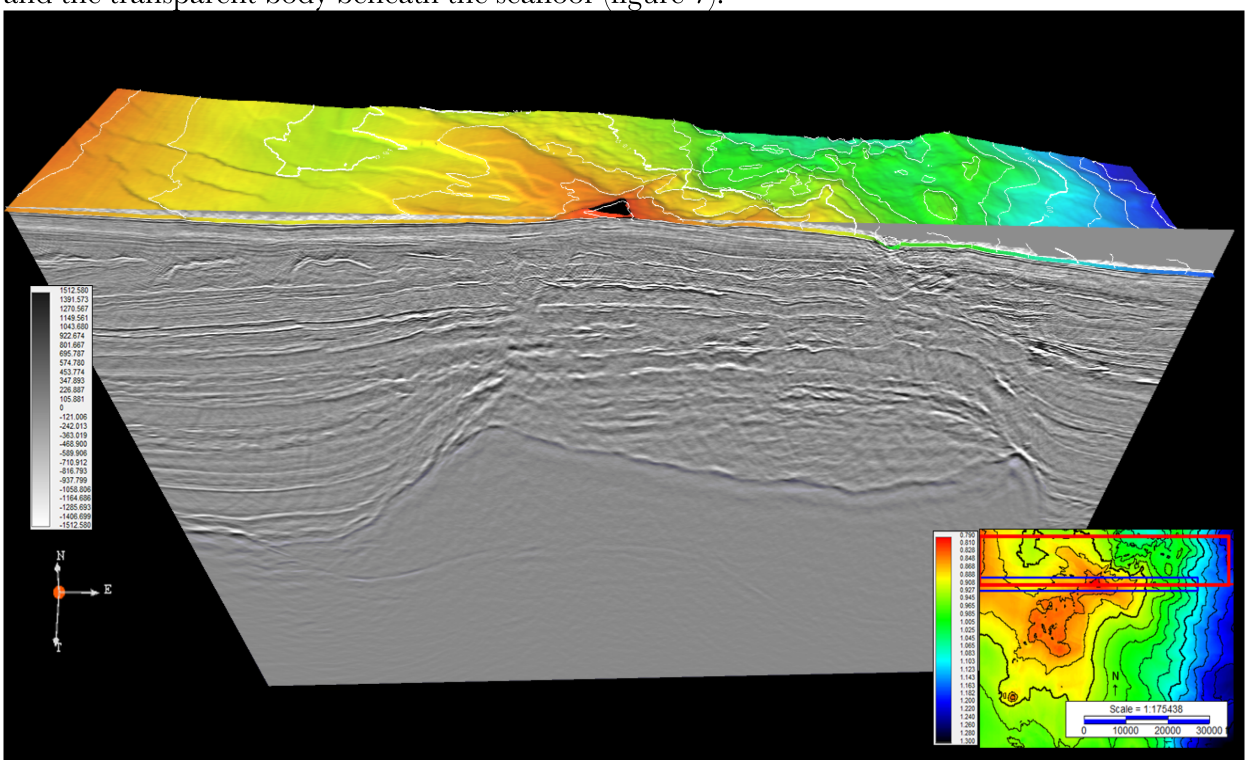

Figure 7: Uninterpreted VuPAK of feature #3. Cross-sectional view shown with overlying topography to connect subsurface geology with topographic expressions. There is bedding preserved above the transparent facies in the subsurface. The red square on the map is the topography imaged in VuPAK while the red line is the seismic line present.

Discussion

When the amplitude of the data is viewed in maps, the streaks of changing amplitude are just artifacts of the seismic survey and are not geologic (figure 2).

Seafloor Feature #1- Mud volcano due to gas venting

Seafloor expulsion feature #1 is interpreted to be a mud volcano gas venting system. Mud volcanoes are usually round and contain a rounded top like the feature presented (Sager et al., 2003). This feature is seen on the amplitude base map as a ring of relatively high impedance contrast with an anomalous center area (figure 2) that is consistent with the impedance contrast of the seafloor which is expected from natural gas seeps (Sager et al., 2003). The lower reflectivity in the center (figure 2) relates to freshly disturbed sediment. The density of this sediment is decreased due to fresh turbidation leading to a lower p-wave velocity causing a lower impedance contrast compared to the denser more lithified sediments on the outer ring of the feature (Roberts et al., 2006). The seismic line view reinforces this idea with some bedding being preserved on the flanks of the mound (figure 8) and the flanks of the transparent area beneath the mound (Wu et al., 2018). It is possible that this transparent area could be a salt diapir or an area of natural gas migration. The relatively flat undisturbed nature of bedding being preserved indicates that the transparent area is not a solid salt diapir but rather gas migrating through bedding via fluid migration pathways. There must also be a large and rapid to moderately rapid supply of fluid or gas in order for this migration pathway to make it all the way to the seafloor without the formation of large chemosynthetic communities (Roberts and Carney, 1997). It is possible that the small topographic feature to the west of the main feature could be a chemosynthetic community due to its slightly positive amplitude anomaly correlated with the gas venting in the vicinity (figures 2 & 8) but some more seafloor imaging and well drilling would need to be done to confirm this hypothesis. This transparency can be seen in salt diapirism, but it is also characteristic of sediments that are not compacted or that are mixed due to fluid and gas migration (Roberts et al., 2006). Since there is still bedding preserved in some of the transparency and a change in amplitude across the feature it is a gas venting system rather than a salt diapir extruding at the surface (figures 2 & 8).

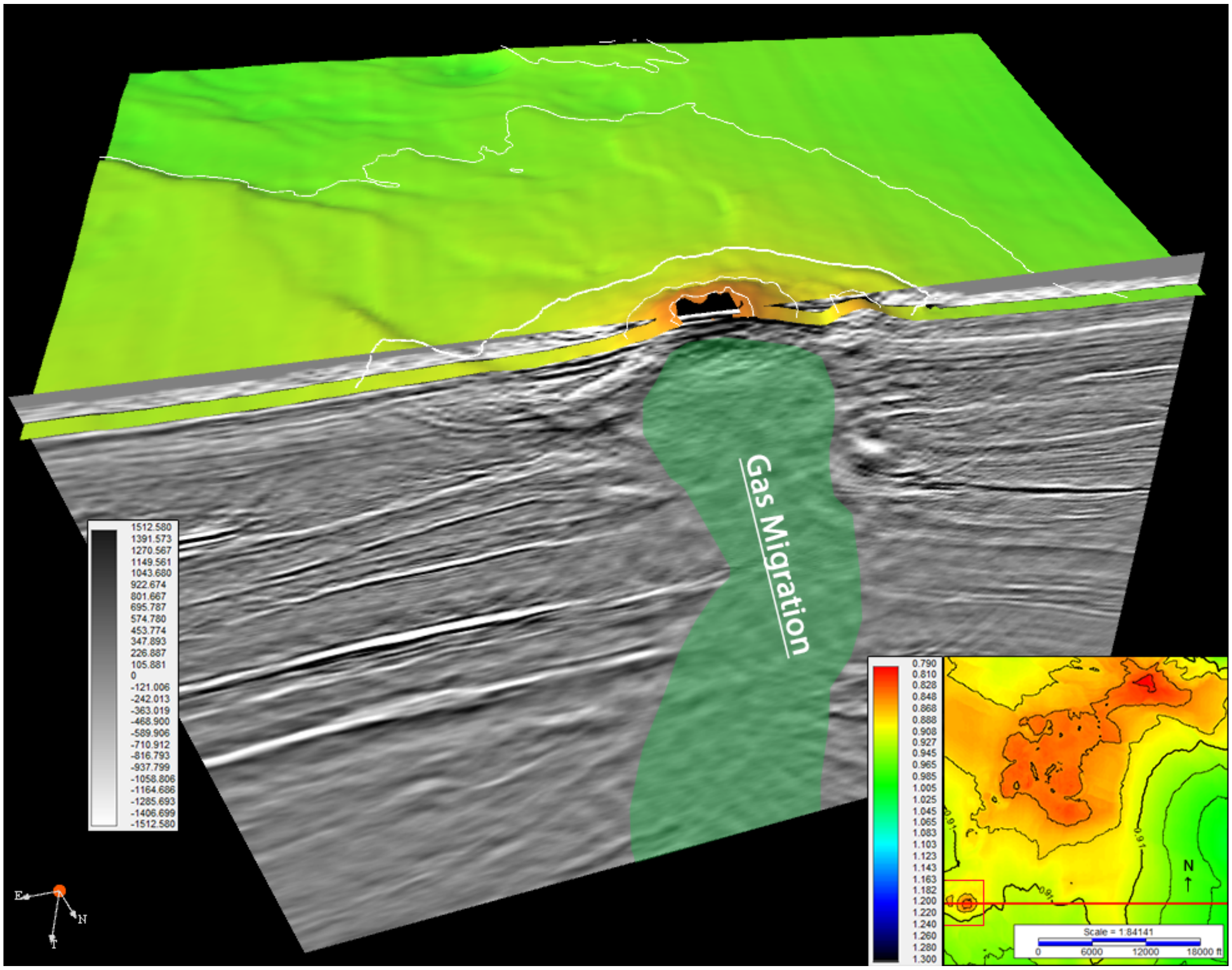

Figure 8: Interpreted VuPAK of feature #1. Cross-sectional view shown with overlying topography to connect subsurface geology with topographic expressions. Gas migration is shown by a transparent reflection less area and is highlighted in green. Some bedding is preserved but most is muddled by gas migration. The red square on the map is the topography imaged in VuPAK while the red line is the seismic line being shown.

Seafloor Feature #2- Salt diapir extruding at the surface

Seafloor expulsion feature #2 may be a salt diapir that is extruding at the surface. This is shown through as very high positive amplitude anomaly in the center of the mounded area (figure 2) which is what one would expect when salt units are present due to the highly conductive nature of salt. Salt has a high P-Wave velocity compared to seafloor sediments which explains the high amplitude anomaly where it outcrops at the surface (Roberts et al., 2006). The classification of a salt diapir is reinforced in the seismic lines by large globular transparent facies that goes all the way to the seafloor. This classification is also reinforced by the folding of beds along the flanks of the diapir (figure 9). It is also reinforced by the ideal that an extruding salt diapir will remain the same shape and build up at the surface (Ela et al.,1994). The size of this feature (figures 3,6 & 10) suggests that there must also be a large volume of salt being supplied in order for that amount salt to be extruding at the seafloor. This is a form of passive diapirism and the diapir is characterized by aggradation of sediment occurring at a faster rate than the rise of the diapir causing a tapered feature (figure 9) that outcrops at the surface (Karam and Mitra, 2016). The substance is seen extruding at the seafloor through a muddled seafloor reflector (figure 9) unlike the seafloor in an area that is undisturbed. The bathymetric map (figure 6) shows radial faults at the surface which are caused by the fluid nature of salt under pressure and the accommodation that occurred in the underlying sediments (Hansen et al., 2005). Radial faulting correlated with the high amplitude anomaly across the feature (figure 2) and transparent seismic facies (figure 9) points to a classification of salt diapirism. There is also a bottom simulating reflector present represented by a strong negative impedance contrast as the solid and dense hydrate turns into a gas phase zone (figure 9). The hydrate zone has been brought upwards due to the conductivity of the salt diapir and the accumulation of free gas is due to the migration of salt through the sediments acting as a pathway for gas migration (Nyamapfumba and Mcmecha, 2012).

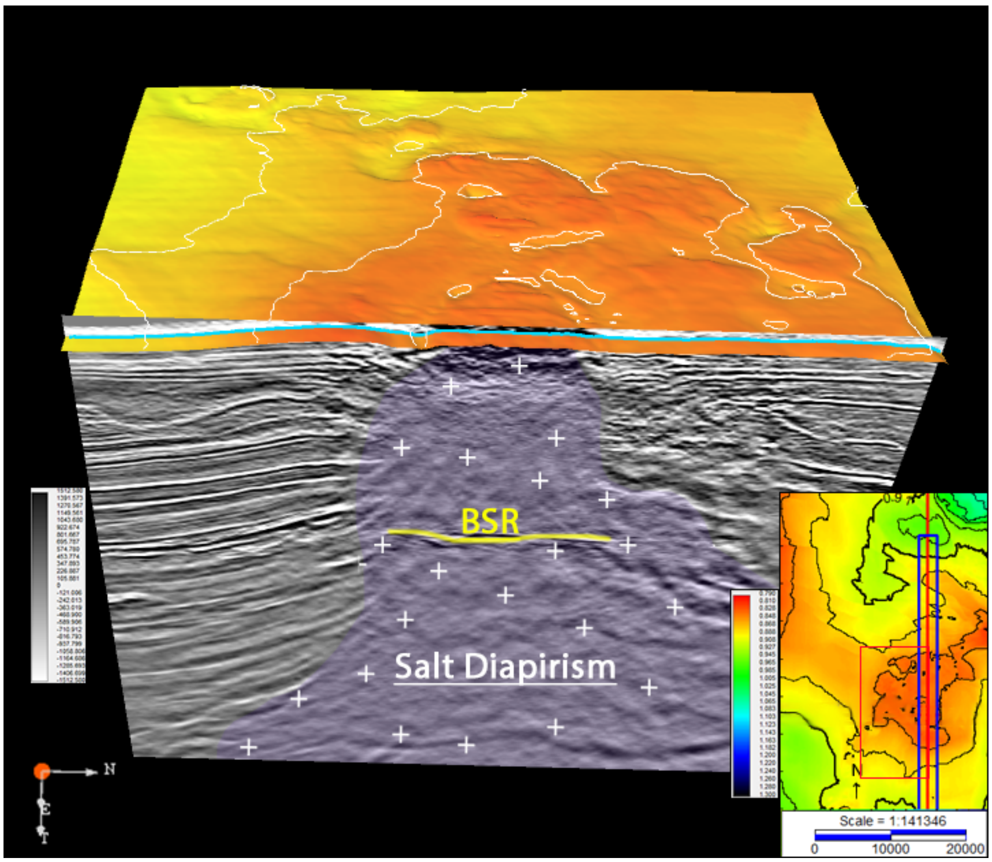

Figure 9: Interpreted VuPAK of feature #2. Cross-sectional view shown with overlying topography to connect subsurface geology with topographic expressions. A Salt Diapir (highlighted in purple) is disrupting bedding in the subsurface and causing topographic relief. There is a strong negative reflector present in the middle of the transparent facies that represents a Bottom Simulating Reflector (BSR). The red square on the map is the topography imaged in VuPAK while the red line is the seismic line being shown.

Seafloor Feature #3- Salt diapirism causing topographic expression

Seafloor feature #3 (figure 10) is an uplifted section of sediments resulting from underlying salt diapirism. The salt diapir causing topographic relief is shown in the seismic line presented as large transparent facies that connects to a fault that is exposed at the seafloor (figure 10). The topographic relief caused by salt diapirism is reinforced by the idea that layers of strong overburden can contain the pressure of the diapir and cause the diapir to spread laterally. This explains how this diapir has a wide range and has caused the faulting which caused the uplift on a northwest to southeast trend (Ela et al.,1994). This main fault and a set of faults can be seen on the bathymetric map (figure 2). The strong overburden in feature #3 comes from very thick units of rock overlying the salt (figure 10) and is the reason this diapir spread out more laterally than the other two features (Koyi, 1998). There are surface relief and surface faults due to the salt tectonics that are shown on the TWT base map (figure 3). The transparent facies under the seafloor and the lack of amplitude anomalies in the area of uplift and faulting fit with this interpretation and the topographic expression is an uplifted portion of the seafloor (figures 2 & 10).

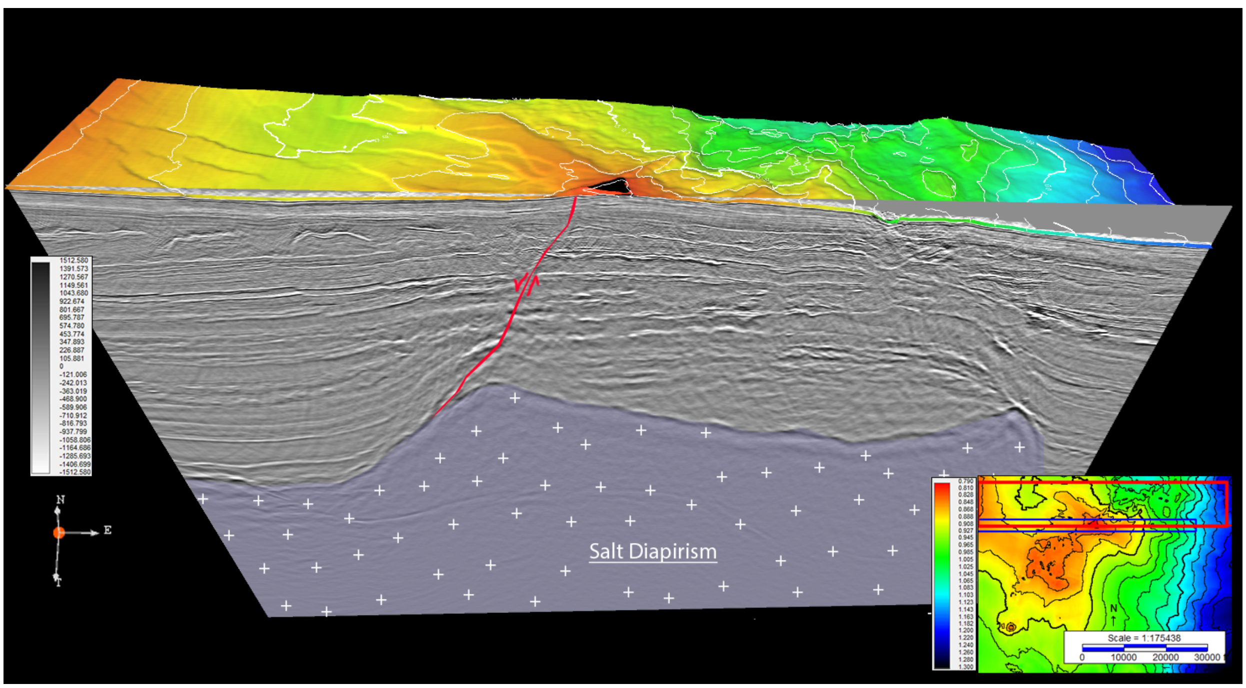

Figure 10: Interpreted VuPAK of feature #3. Cross-sectional view shown with overlying topography to connect subsurface geology with topographic expressions. Above the salt diapir there is relatively parallel bedding. A major fault is shown above the salt diapir that has caused uplift of the seafloor creating the present-day topography. The red square on the map is the topography imaged in VuPAK while the red line is the seismic line being presented.

Connection of seafloor features #1, #2 and #3

The features chosen for analysis are all part of a connected salt diapir system. In the subsurface the transparent area salt facies are all connected (figures 11 & 12). A wide variety of features can arise from the plastic deformation of salt in the subsurface when confined by overburden. The system studied here has caused gas migration resulting from pathways created by salt diapirism in feature #1 (figures 8, 11 & 12). A portion of the diapir outcrops at the seafloor and can be seen as an amplitude anomaly and a topographic plateau in feature #2 (figures 2, 3 & 9). The same system has caused a major normal fault that extends from the top of the salt diapir to the seafloor and has resulted in a topographic high for the region resulting from the movement of the diapir in feature #3 (figures 10 & 11).

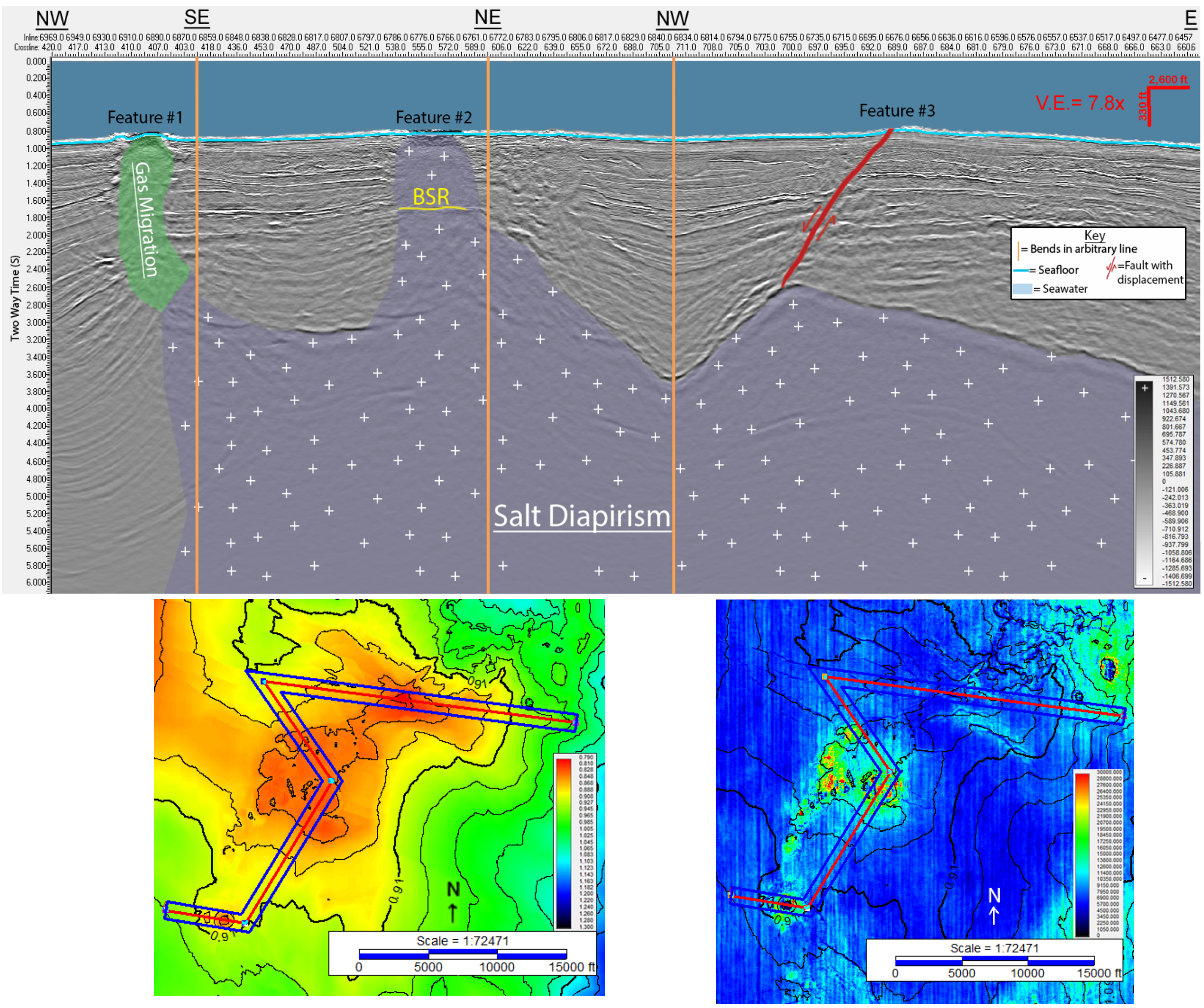

Figure 11: Interpreted seismic line containing features #1, #2 & #3. A Salt Diapir system (highlighted in purple) is disrupting bedding in the subsurface and causing topographic relief within features #2 & #3. The same salt diapir is also acting as a pathway for gas migration in feature #1. There is a strong negative reflector present beneath feature #2 that represents a Bottom Simulating Reflector (BSR). The red line on the base maps is the seismic line imaged.

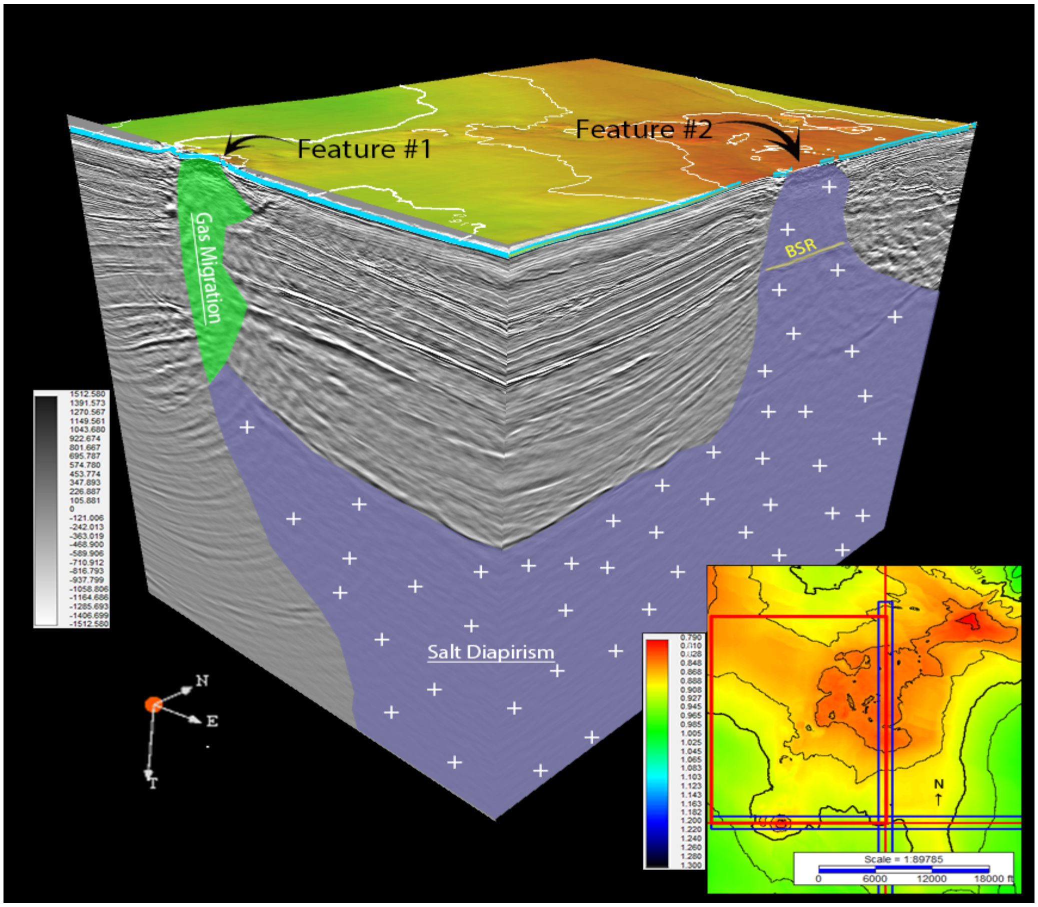

Figure 12: Interpreted VuPAK of features #1 & #2. 3D Cross-sectional view shown with overlying topography to connect subsurface geology with topographic expressions of features #1 & #2. A Salt Diapir (highlighted in purple) is disrupting bedding in the subsurface and causing topographic relief within feature #2 and acting as a pathway for gas migration in feature #1. There is a strong negative reflector present beneath feature #2 that represents a Bottom Simulating Reflector (BSR). The red square on the map is the topography imaged in VuPAK while the red line is the seismic line being shown.

Table 2: Attributes of Features Identified in this Study

Feature	Latitude (°)N	Longitude (°)E	Inline	Crossline	Geologic Interpretation
#1	28.02662674	-89.72754242	6896	407	Mud volcano gas venting system
#2	28.06526654	-89.69417687	6766	564	Salt diapir extruding at the seafloor
#3	28.09518187	-89.6606421	6675	690	Topographic expression caused by an underlying salt diapir

CONCLUSIONS

All three features were related to an underlying salt deposit (figures 11). If drilling were to be done in this area more research would need to be done as these features are expansive and cover most of the area close to the said features. Seafloor feature #1 is interpreted to be a mud volcano gas venting system. The change in amplitude across the feature was the anomaly that suggested this conclusion (figure 2). The seismic line reinforces this interpretation by imaging a large transparent area underlying the mounded surface with some bedding preserved (figure 8 & 11). Seafloor feature #2 was determined to be a salt diapir extruding at the surface. This was determined by the observation of a positive amplitude anomaly across the amplitude base map that would be consistent with salt being present (figure 2). The seismic line reinforces this interpretation by imaging a large transparent area that is present all the way to the seafloor with bedding on its flanks being slightly folded upward (figures 9 & 11). Seafloor feature #3 was determined to be a portion of the seafloor that was uplifted by an underlying salt diapir. This was determined by a change of topography associated with no amplitude anomaly on the amplitude base map (figure 2). The seismic line reinforces this by showing a major normal fault in layers of sediments with a large transparent body underlying these layers that corresponds to the relief shown on the seafloor (figures 10 &11).

Recommendations for Future Work

There are a few recommendations for further work with in this area. This area seems to have an active natural gas fueled mud volcano and a BSR within the salt diapir. This area could be explored for potential hydrocarbon reserves. In order to determine if this area is a viable hydrocarbon play more imaging must be done and wells with logs would need to be drilled in order to confirm that hydrocarbons are actually present. If hydrocarbons are present more drilling operations would be needed to determine what type of lithologies would be encountered in drilling throughout the surveyed area. Gamma ray, resistivity and sonic logs are some examples of well logs that would need to be done in order to correlate stratigraphic layers across the data set. More 3D seismic interpretation incorporating well logs would also need to be done to determine the amount of hydrocarbons in this area and where to try to extract them. To determine drilling risks the salt diapir and the major normal fault would need to be mapped across the survey and correlated with the well logs that were taken.

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